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Wind turbines at night: acoustical practice and sound research

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Sound levels near a wind turbine park at night were much higher then expected. This is caused by strong winds at hub height especially when at ground level there is little wind, as is quite usual at night. This common and wellknown meteorological effect has not yet been recognized with respect to wind turbine noise.
To determine turbine sound power levels we had to deviate from the recommended standard measurement procedure. Without park operator co-operation it was impossible to operate just one turbine or no turbine at all. Also a hard, reflective board as recommended was impractical or impossible to use. Impulsiveness is usually determined with a single turbine in operation. We conclude that sound pulses, not clearly audible in the wind park itself, are caused by the interaction of several turbines.
The case described here shows that calculation models should regularly be checked for correctness, especially in new situations/applications and where a strong community reaction may indicate a model does not cover reality. We also recommend that it must always be possible to check calculated immission levels by immission measurements, with or without operator co-operation. This does not only apply to the case of wind turbines.
Although standard procedures are necessary and useful, a negative effect is it makes citizens more dependent on experts. The cost of access to expertise is an important threshold to objective judgement.

1. INTRODUCTION

In 2001 the German wind park Rhede was put into operation just 400 m from the Dutch border. Local authorities as well as residents at the Dutch side had opposed the construction of the 17 wind turbines because of the effects on landscape and environment: with 98 m hub height the 1.8 MW turbines would dominate the skyline of the early 20th century village of Bellingwolde and introduce noise in the quiet area. With the turbines in operation residents at 500 m and more from the wind park found the noise (and flicker shadow, which will not be dealt with here) worse than they had expected. The wind park operator declined to take measures as acoustic reports showed that German as well as Dutch noise limits were not exceeded. When the residents brought the case to a German court, they failed on procedural grounds. For a Dutch court they had to produce arguments that could only be provided by experts.

Science Shops are specifically intended to help non-profit groups by doing research on their behalf. For the Science Shop for Physics in Groningen noise problems constitute the majority of problems that citizens, as a group or individually, come up with. Although the aim of sound research is the same as for acoustic consultants –to quantify sound levels relevant for annoyance- the customers are different: consultants mostly work for the party responsible for the sound production, whereas the Science Shop mostly works for the party that is affected by the sound. This may lead to different research questions. In the case of wind park Rhede a consultancy will check the sound production of the turbines and check compliance of the calculated sound immission level with relevant limits. The Science Shop however, taking the strong reaction from the residents as a starting point, wanted to check whether the real sound immission agrees with the calculated one and whether sound character could explain extra annoyance.

Earlier we showed in a Dutch magazine, on the basis of 30 acoustic reports, that acoustic consultants tended to rely too much on information from their customers, even when they had reason to be critical about it [8]. As consultant's customers are usually noise producers and authorities: the point of view of those that are affected by noise is not usually very prominent. The present paper shows that for wind turbines a similar case can be made.

2. RESULTS FROM THE WIND PARK RHEDE

The results of the investigation of the sound from the wind park Rhede are given in a Dutch report and an English paper presented to the JSV [1, 2] (there are efforts to produce a German translation of the report). Here the results will be dealt with briefly. The main cause for the high sound level perceived by residents is the fact that wind speeds at night can, at 100 m height, be substantially higher than expected. For acoustic purposes prediction of the wind speed at hub height is based on the wind speed v_{ref} at the reference height for wind speed measurements (h_{ref} = 10 m), extrapolated to a wind speed v_h at height h with the well known and widely used formula for the logarithmic wind profile: $v_h = v_{ref} \cdot \log(h/z)/\log(h_{ref}/z)$. This profile may be used only implicitly when the relation between turbine sound power level and v_{ref} valid for daytime conditions is used for night time conditions. The logarithmic profile depends only on roughness length z, not on atmospheric conditions. It should be valid for a neutral, *i.e.* heavily overcast and/or very windy atmosphere, not for a stable atmosphere as is usual in night time. At night, given a specific wind speed at reference height, the wind speed at greater heights will be higher than expected from the logarithmic profile (or rather: given a specific high wind, the wind speed at lesser heights is lower). A well known observation is that at night the wind subsides. This is not caused by high, geostrophical winds (as these are not determined by diurnal influences but by the distribution of high and low pressure areas) but by atmospheric stability caused by radiative cooling. When at night cooling sets in the wind speed close to the ground is indeed reduced and the wind speed at hub height is higher than expected from the logarithmic wind profile. As a consequence a wind turbine produces more sound then expected from the wind speed at reference height. As measured immission levels near the wind park Rhede show, the discrepancy may be very large: sound levels are up to 15 dB (!) higher than expected at 400 m from the wind park. At a distance of 1500 m actual sound levels are 18 dB higher than expected, 15 dB of this because of the higher sound emission and 3 dB because sound attenuation is less than predicted by the sound propagation model. The important point is not so much that the maximum measured sound level is higher than the maximum expected sound level (it was, around +2 dB, but this was not an effect of the wind speed profile). The point is that this maximum does not only occur at high wind speeds as expected, accompanied by high wind induced ambient sound levels, but already at relatively low wind speeds (4 m/s at 10 m height) when there is little wind at the surface and therefore little wind induced background sound. Thus, the discrepancy of 15 dB occurs at quiet nights, but yet with wind turbines at almost maximum power. This situation occurs quite frequently.

A second effect that adds to the sound annoyance is that the sound has an impulsive character. The primary factor for this is the well known swishing sound caused by the pressure fluctuation when a wing passes the turbine mast. For a single turbine these 1 – 2 dB broad band sound pressure fluctuations would not classify as impulsive. When several turbines operate nearly synchronously the pulses however may occur in phase: two equal pulses give a doubling in pulse height (+3 dB), three a tripling (+5 dB). Several low magnitude pulse trains thus cause sound with an unexpected, relatively strong impulsive character whenever they synchronise. The sound then resembles distant pile driving or, as a resident said: 'an endless train'. Synchronisation here refers to the sounds that the wind turbines contribute at the immission point. In the wind park we never heard the impulsiveness.

3. EARLY WARNINGS OF NOISY WIND TURBINES?

One may wonder why the strong effect of the nightly wind profile or the pulselike sound was not noticed before. In the 1998 publication IEC 16400 again only the neutral logarithmic wind profile is used [3]. And even in 2002 a Dutch report stated in a general way that wind turbine sound is not impulsive [7].

There have been some warnings. For example, in 1998 Rudolphi concluded from measurements that wind speed at 10 m height is not a good measure for the sound level: at night the (58 m hub height) turbine sound level was 5 dB higher than expected [4]. Since several years residential groups in the Netherlands, and probably abroad as well, complained about annoying turbine sound at distances where they are not even expected to be able to *hear* the sound. Recently Pedersen *et al* found that annoyance was relatively high at (calculated!) sound immission levels below 40 dB(A) [5] where one would not expect strong annoyance.

As wind turbines become taller, the discrepancy between real and expected levels grows and as more tall wind turbines are constructed complaints may become more widespread. In the Netherlands residents near the German border were (apart from one single tall turbine elsewhere) the first Dutch to be acquainted with turbines of 100 m hub heights.

It may be that earlier discrepancies between real and projected sound immission were not sufficient to evoke strong community reactions and that only recently turbines have become so tall that the discrepancy now is intolerable.

There are other reasons that early warnings perhaps did not make much impression. One is that sound emission measurements are usually done in daytime. It is hard to imagine the sound would be very different at night time, so (almost) no one did. Until some years ago, I myself could not imagine how people could hear wind turbines 2 km away when at 300 to 400 m distance the (calculated) immission level was, for a given wind speed, already equal to the ambient background sound level (L_{95}).

What is probably also a reason is the rather common attitude that 'there are always people complaining'. Complaints are a normal feature, not a reason to re-investigate. Indeed Dutch noise policy is not to prevent any noise annoyance, but to limit it to acceptable proportions. Added to this is a rather general conviction of Dutch authorities and consultants that routine noise assessment in compliance with legal standards *must* be correct. If measurements are performed it is to check actual *e*mission levels –usually in normal working hours, so in daytime. It is quite unusual to compare the calculated sound *im*mission from a wind turbine (park) with measured immission levels (so unusual that it is likely that we were the first to do so).

A third reason may be partiality to the outcome of the results. Wind turbine operators are not keen on spending money that may show that sound levels do not comply with legal standards. And if, as expected, they do comply, the money is effectively wasted. Apart from this, we have the experience that at least some organisations that advocate wind energy are not interested in finding out why residents oppose wind parks.

4. THE USE OF STANDARD PROCEDURES

Although our objective was to measure immission sound levels, we also wanted to understand what was going on: if levels were higher than expected, was that because emission was higher or attenuation less? We therefore also measured sound emission as a function of rotational speed of the variable speed turbines. An interesting point that came up with the emission measurement was that compliance with the used standard [6] was impossible. As the park operator withdrew the co-operation that was previously promised, we had to measure emission levels with the full park in operation, as we obviously did not have the means to stop all turbines except the one to be measured, as the standard prescribes. To measure ambient background sound level, even the last turbine should be stopped.

In compliance with the standard the emission should be measured within 20% of the distance to the turbine equal to hub height + wing span. However, to prevent interference from the sound from other turbines the measurement location had to be chosen closer to the turbine.

The primary check on the correctness of the distance (*i.e.* not too close to other turbines) was by listening: the closest turbine should be the dominant source. If not, no measurement was done, and usually a measurement near another turbine was possible. Afterwards we were able to perform a second check by comparing the measured sound immission of the wind park at a distance of 400 m with the level calculated with a sound propagation model with the measured emission level of all (identical) turbines as input. The calculated difference between a single turbine sound power level and the immission level was 58.0 dB (assuming a constant spectrum this is irrespective of the power level itself). The measured average difference was 57.9 dB, with a maximum deviation of individual measurement points of 1.0 dB. In fact, from our measurements one may conclude that, to determine turbine sound power level, it is easier and cheaper to measure total sound emission at some distance from a wind park then measuring separate turbines. And in many nights the wind induced ambient sound, that easily spoils daytime measurements, is not an important disturbance!

Using a 1 m diameter round hard board, in compliance with the standard, was quite impractical and sometimes impossible. *E.g.* in one place potato plants would have to be cleared away, in another one would have to create a flat area in clumps of grass in a nature reserve, both unnecessarily. Instead of the large board we used the side (30x44 cm^2) of a plastic sound meter case. We convinced ourselves that this was still a good procedure by comparing sound levels measured on the case on soft ground with sound levels measured just above a smooth tarmac road surface a few meters away, both at the same distance to the turbine as in the other measurements: there was no difference.

Whether a turbine produces impulsive sound is determined by listening to and measuring the sound near a single turbine (along with measurements to determine sound power and spectral distribution). In the Netherlands impulsivity is judged subjectively (by ear), not by a technical procedure as in Germany. Interestingly, in Dutch practice only an acoustician’s ear seems reliable, though even their opinions may disagree. Judgement can be supported with a sound registration showing the pulses. From our measurements the impulsive character can be explained by the interaction of the sound of several turbines. Even at a time the impulsive character can be heard near residents' dwellings, it cannot (never?) clearly be heard close to the turbines in the wind park. So here also there was need to do measurements where people are actually annoyed, and not to rely on source measurements only, certainly not from one turbine.

When noise disputes are brought to court, it is clearly advantageous to have objective procedures and standards to assure that the technical quality, which can hardly be judged by non experts, is sufficient and therefore the results are reliable. In the case made here a standard may however be non-applicable for valid reasons. Already however the *e*mission measurements are contested on procedural grounds (*viz.* we have not complied to the standard). As a matter of fact the *im*mission sound levels were the primary research targets and we did not really need the sound *e*mission measurement results, so the opposition does not seem very relevant.

The tendency to put all noise assessment into technical standard procedures has the disadvantage that it is hardly possible for non experts, such as residents, to bring other arguments to court. They, the annoyed, will have to hire an expert to objectify their annoyance. This is not something every citizen can afford.

5. MODELLING VERSUS MEASUREMENTS

Being able to calculate sound levels from physical models is certainly a huge advantage over having to do measurements (if that, indeed, is possible) especially as in practical situations conditions keep changing and other sounds disturb the measurements. Because of its obvious advantages models have become far more important for noise assessment than measurements. In the Netherlands usually sound emission measurements are carried out close to a source to determine sound power levels. Then, with the sound power level, the immission level is calculated, usually on façades of residences close to the sound source. It is not common to measure immission levels in the Netherlands; in some cases (*e.g.* railway, aircraft noise) there is not even a measurement method (legally) available to check calculated levels.

A physical model however is never the same as reality. As was shown above, the widely used model for sound production from wind turbines is implicitly based on a specific wind profile. This profile is not correct at night, although the night is the critical period for wind turbine noise assessment. Also attenuation with distance is overestimated for distances over 0,5 km.
Even a perfect physical model will not reproduce reality if input values are not according to reality. An example is to apply sound power levels from new sources (cars, road surfaces, aeroplanes, mopeds, vacuum cleaners, etc.), maybe acquired in a specific test environment, to real life situations and conditions. In a wind park south of the wind park Rhede a turbine produced a clearly audible and measurable tonal sound, probably caused by a defect on a wing. It is very hard for residents to convince the operator and authorities of this annoying fact, partly because all experts say that modern wind turbines do not produce tonal sound.
Incorrect models and incorrect input may well occur together and be difficult to separate. It should be important that calculation models are regularly checked for correctness. Situations where (strong) complaints arise may indicate just those cases where models do not cover reality.

6. CONCLUSION

In modelling wind turbine sound very relevant atmospheric behaviour has been ‘overlooked’. As a consequence, at low surface wind speeds such as often occur at night, wind turbine noise immission levels may be up to 15 or 18 dB higher than expected. The discrepancy between real and modelled noise levels is greater for tall wind turbines. International models used to assess wind turbine noise on dwellings should be revised for this atmospheric effect.

A discrepancy between noise forecasts and real noise perception, as a result of limited or even defective models, cannot always be avoided, even not in principle. Its consequences can however be minimised if immission levels are measured at relevant times and places. This relevancy is also determined by observations of those affected. It should always be possible to check noise forecasts by measurement.

For wind turbine noise (and other noise sources) standard measurement procedures require co-operation of the operator to be able to check emission sound levels. This introduces an element of partiality to the advantage of the noise producer. This is also generally a weak point in noise assessment: the source of information is usually the noise producer. There should always be a procedure to determine noise exposure independent of the noise producer.

Standard technical procedures have the benefit of providing quality assurance: when research has been conducted in compliance with a standard procedure lay persons should be able to rely on the results. It may however also have a distinct disadvantage for plain people opposing a noise source: when an assessment is not in agreement to a standard procedure is may not be accepted in court, regardless of the content of the claim. A negative side effect is the resulting dependency on legal as well as acoustical experts. If citizens are forced to use expert knowledge, one may argue that they should be given access to that knowledge. An important threshold is the cost of that access.

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